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Advanced Environmental Barrier Coating Development and Testing for SiC/SiC Ceramic Matrix Composites

Dongming Zhu

Structures and Materials Division
NASA John H. Glenn Research Center
Cleveland, Ohio 44135

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Dennis S. Fox, James DiCarlo, James L. Smialek, Janet Hurst, Bryan Harder, Ram Bhatt, Nate Jacobson, Yoshiki Yamada, Louis Ghosn, Martha H. Jaskowiak, Michael Halbig

Durability and Protective Coatings Branch (Chief: Joyce A. Dever), Ceramic Branch (Chief: Joseph E. Grady), and Life Prediction Branch (Chief: Steve M. Arnold)

Collaborators: Directed Vapor Technologies, International; Sulzer Metco US; Praxair; GE Aviation; Hypertherm; Ceramatec, Inc.

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Outline

- **Environmental barrier coating system development: needs and challenges**
- **Advanced environmental barrier coating systems for CMC airfoils and combustors**
  - NASA coating development goals
  - Current turbine and combustor EBC coating emphases
- **Development of next generation environmental barrier coatings**
  - Advanced processing
  - Advanced CMC-EBC rig testing
  - Subelement and subcomponent demonstrations
- **Summary**

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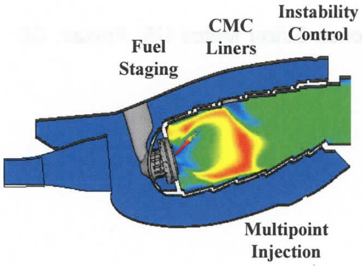
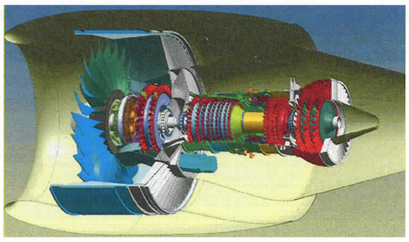
NASA Environmental Barrier Coating (EBC) - Ceramic Matrix Composite (CMC) Program Overview

- **NASA Fundamental Aeronautics Program (FAP)**: Next generation high pressure turbine airfoil environmental barrier coatings with advanced CMCs
  - N+3 generation (2020-2025) with advanced 2700°F CMCs/2700-3000°F EBCs (uncooled/cooled)
- **NASA Environmentally Responsible Aviation (ERA) Program**: Advanced environmental barrier coatings for SiC/SiC CMC combustor and turbine vane components, technology demonstrations in engine tests
  - N+2 generation (2020-2025) with 2400°F CMCs/2700°F EBCs (cooled)



Low emission combustor



High Pressure Turbine CMC vane and blade

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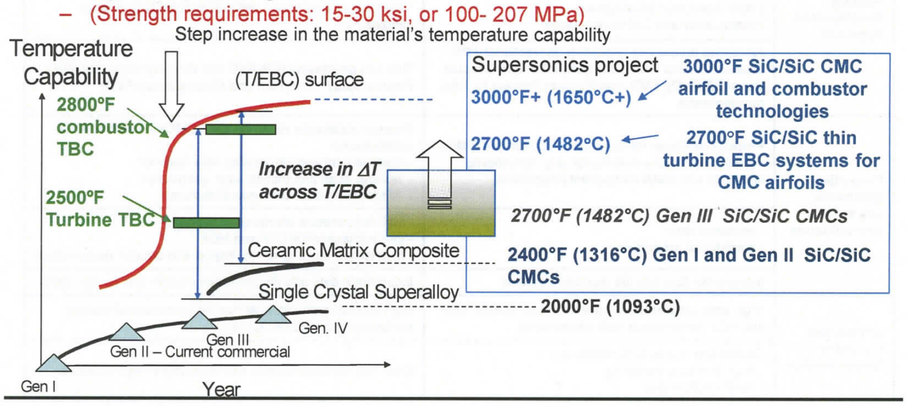
NASA EBC and CMC System Development

- Emphasize temperature capability, performance and *long-term* durability
- Develop innovative coating technologies and life prediction approaches
- Meet 9,000 h supersonic engine and 1000 h subsonic engine hot-time life requirements
  - Recession: <5 mg/cm^2 per 1000 h
- Highly loaded EBC-CMCs capable of thermal and mechanical (static/low cycle and dynamic) loading
  - (Strength requirements: 15-30 ksi, or 100- 207 MPa)



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Environmental Barrier Coating Development: Challenges and Limitations

- **Current EBCs limited in their temperature capability, water vapor stability and long-term durability, especially for advanced high pressure, high bypass turbine engines**
- **Advanced EBCs also require higher strength and toughness**
  - In particular, resistance to combined high-heat-flux, engine high pressure, combustion environment, creep-fatigue, loading interactions
- **EBCs need improved erosion, impact and calcium-magnesium-alumino-silicate (CMAS) resistance and interface stability**
  - Critical to reduce the EBC Si/SiO$_2$ reactivity and their concentration tolerance
- **EBC-CMC systems need advanced processing for realizing complex coating compositions, architectures and thin turbine configurations for next generation high performance engines**
  - Advanced high temperature processing of high stability nano-composites using advanced Plasma Spray, Plasma Spray - Physical Vapor Deposition, EB-PVD and Directed Vapor EB-PVD, and Polymer Derived Coating processing

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NASA EBC Development Objectives and Approaches

	CMC combustor EBC	CMC Turbine Vane/Blade EBC
Overall Objectives	2700-3000°F capable EBC <15 mil thickness plasma-sprayed or hybrid plasma-spray-EB-PVD processing on 2400°F Prepreg MI Gen II SiC/SiC CMC system > 1000 hr durable life	2600-2700°F capable EBC <5-10 mils in thickness thin film processing on 2400°F Prepreg MI Gen II SiC/SiC and CVI woven high strength SiC/SiC CMC systems 1000 hr durable life
Coating Development Approach	High stability (recession < 5 mg/cm^2 in 1000 hr) Low thermal conductivity (<1.0 W/m-K)	High stability (recession: 5-10 mg/cm^2 specific weight loss, and/or less than 20 micrometer thickness in 1000 hr)
	Multilayer coating systems 2700F bond coat development Fretting wear and CMAS resistance	* Thin, multi-component, multilayer coating systems * Advanced bond coats: HfO_2-Si composite and other candidates
	Advanced processing (including conventional APS, Triplex-Pro APS, Thin EBC DVM APS, and Directed Vapor EB-PVD); PVD, and Polymer Derived for EBC developments	Thin film processing (EB-PVD and Directed Vapor EB-PVD, Plasma Spray –Thin Film and Plasma Spray-PVD)
Properties Databases, Life Models and Validation	Property database for combustor EBC-coated CMCs - specimens AND subelements (e.g. film-cooling elements and metal component integration)	Property databases for airfoil EBC-CMCs - coupons AND subelements: - impingement and film cooling hole features - leading edge and trailing edge geometries - reinforcement rib and endwall features
	- recession data - mechanical properties	- high temperature interlaminar strength - thermomechanical LCF and HCF - high temperature dynamic, impact and erosion performance
	Incorporate data into life prediction models	Incorporate data into life prediction models and design tools
Component Durability Demonstration	High temp subelement long-term creep rupture, LCF and HCF performance with attachments	High thermal gradient, heat flux, and mechanical loading performance of coated systems
	Coated liner systems durability in: - high pressure burner rig - NASA ASCR test	CMC turbine vane viability and durability in high pressure

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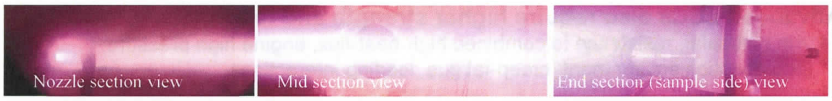
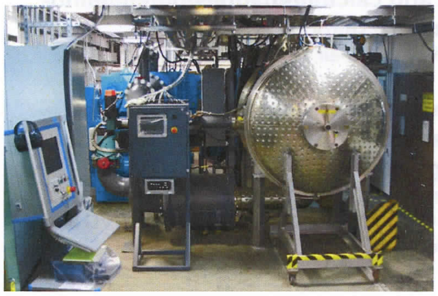
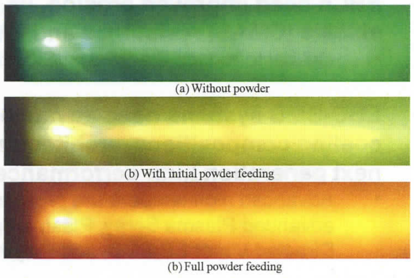
The Development of Plasma Spray - Physical Vapor Deposition (PS-PVD) for CMC Airfoil Coating Processing

– Established for next-generation SiC/SiC CMC turbine airfoil coating processing
- Currently focusing on several advanced model EBC systems processing and evaluation
- Aiming at better understanding processing-property relationship for improving coating performance




NASA Hybrid PS-PVD coater system



High enthalpy plasma vapor stream for efficient and complex thin film coating processing

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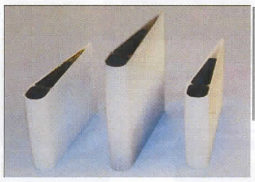
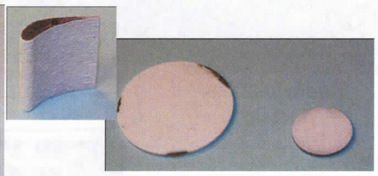
Development of *Directed Vapor* Electron Beam - Physical Vapor Deposition (EB-PVD) for NASA CMC Combustor and Turbine Airfoil Environmental Barrier Coating Processing

- In collaboration with Directed Vapor Technologies, NASA has developed turbine airfoil environmental barrier coating compositions and Directed Vapor EB-PVD processing
- Advanced coatings processed for higher TRL ERA combustor and turbine component EBCs (TRL 4-5)

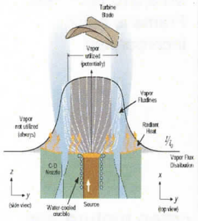
NASA HfO_2-Si bond coat on SiC/SiC

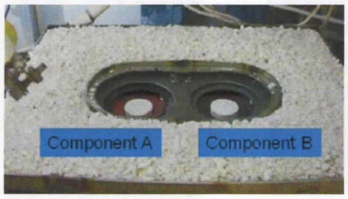
NASA Hybrid EBC on SiC/SiC



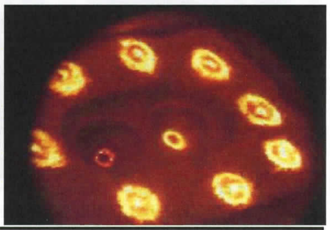


Advanced multi-component and multilayer turbine EBC systems





Directed Vapor Processing Systems



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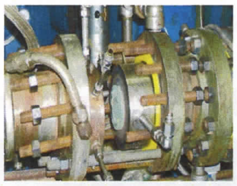
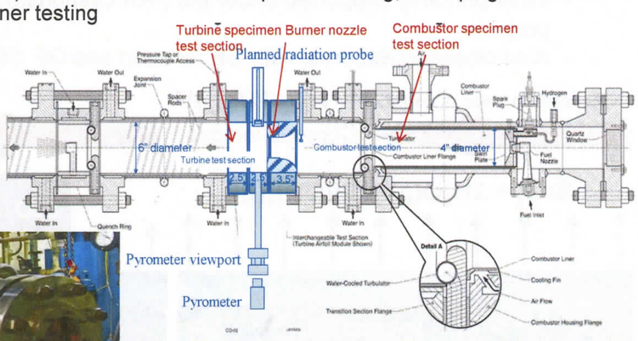
Advanced High Pressure Burner Rig Testing Capabilities Established for Turbine Airfoil and Combustor CMC-EBC Testing

- Jet fuel & air combustion with mass air flow 2.0 lb/s and gas temperature 3000°F+
- Adjustable testing pressures from 4 to 16 atmospheres, independent controls of sample temperature, testing pressure, and gas velocity
- 24-30 KW cooling air heater system for up to 1200°F cooling air (upgraded to 40 KW planned)
- Up to 850 m/s combustion gas velocity in the turbine testing section
- Cooled, pressurized (600 psi) subelement and subcomponent testing, air impingement cooled combustor segments and liner testing





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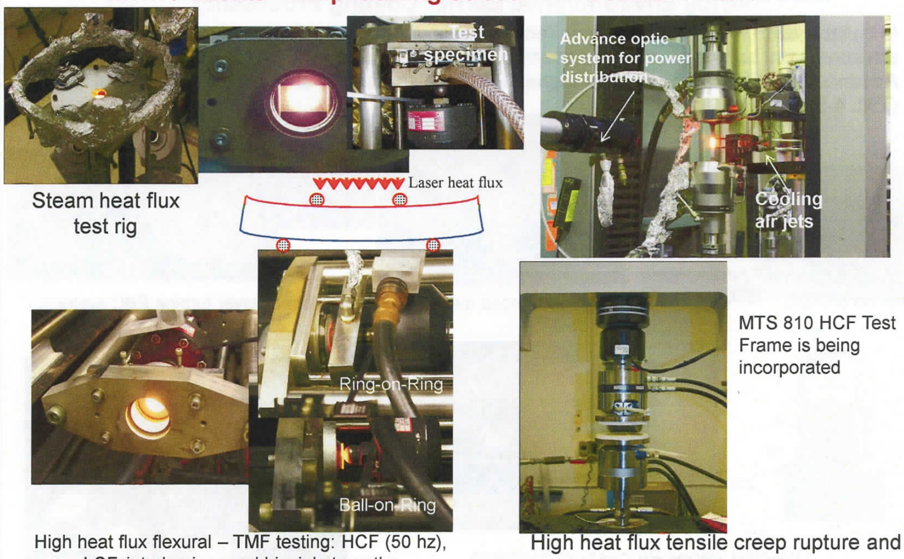
NASA Laser Heat Flux and Mechanical Testing in Simulated Engine Environments – Emphasizing Stress - Environment Interactions



High heat flux flexural – TMF testing: HCF (50 hz), LCF, interlaminar and biaxial strengths

High heat flux tensile creep rupture and TMF and testing

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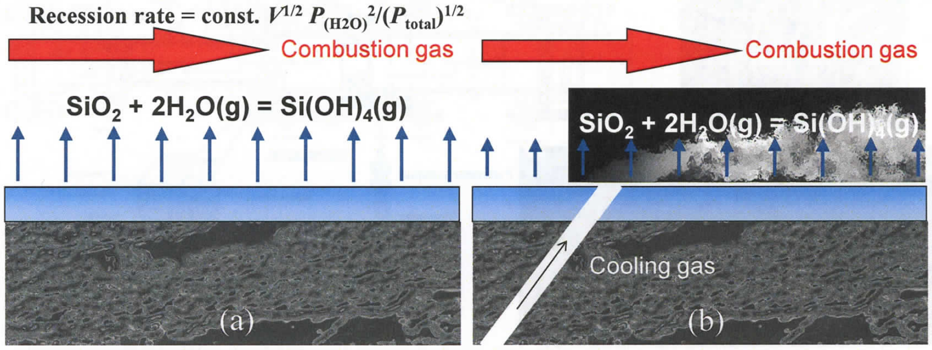
SiC/SiC and Environmental Barrier Coating Recession in Turbine Environments

- **Recession of Si-based Ceramics**
  (a) convective; (b) convective with film-cooling
- **Advanced rig testing and modeling** (coupled with 3-D CFD analysis) to understand the recession behavior in High Pressure Burner Rig
  - Work primarily supported under the ERA Combustor and FAP Supersonics projects
  - Also closely collaborate with GE Aviation and GE Global Research

Recession rate = const. $V^{1/2}\, P_{(H2O)}{}^{2}/(P_{total})^{1/2}$



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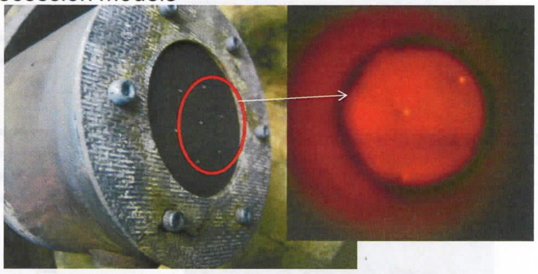
High Pressure High Velocity SiC/SiC Recession Studies Under Film Cooling Conditions

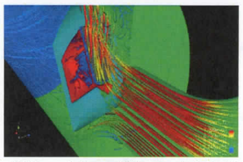
—Determine recession under very high pressure and high velocity – impingement recession completed at 2400F up to 16 atm pressure and 200 m/s gas velocity

— Incorporated both impingement and impingement + film cooled test capabilities

— Validating 3D CFD modeling capabilities

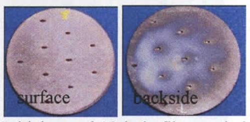
— Establishing comprehensive recession models





The CFD modeling of film cooled CMC included 7, 10 and 17 hole subelements, and water vapor fractions

Initial tested 7-hole film cooled CMC specimen



Initial tested 10-hole film cooled CMC specimen

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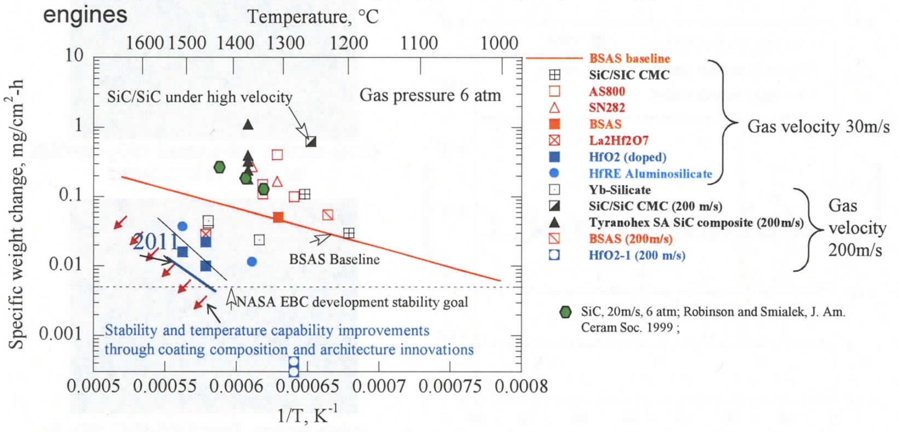
Environmental Stability of Selected Environmental Barrier Coatings Tested in NASA High Pressure Burner Rig

— EBC stability evaluated on SiC/SiC CMCs in high velocity, high pressure burner rig environment

— Stability gaps exist for future high bypass, high operating pressure ratio engines



Stability of selected coatings systems

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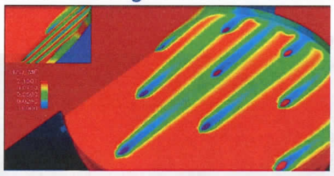
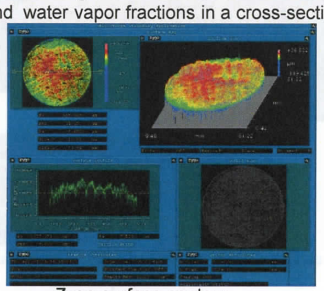
Recession of Film-Cooled SiC/SiC Specimens under NASA High Pressure Burner Rig

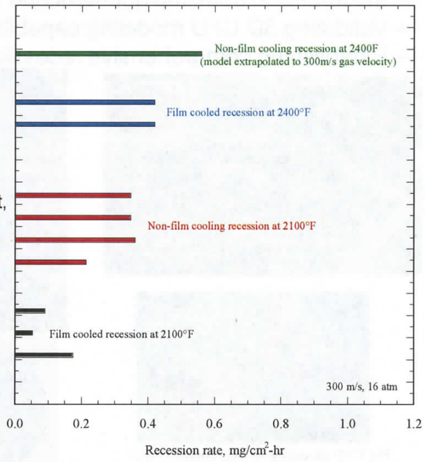
— A 10 hole film-cooled SiC/SiC specimen tested with the cooling air heater operating at 1100°F and CMC, 16 atm testing pressure, 0.085 lb/s cooling air flow in the High Pressure Burner Rig



The CFD modeling of a film cooled CMC 10 hole subelement, and water vapor fractions in a cross-section view



Zygo surface contour



High temperature recession kinetics for film-cooled and non-film cooled SiC/SiC specimens

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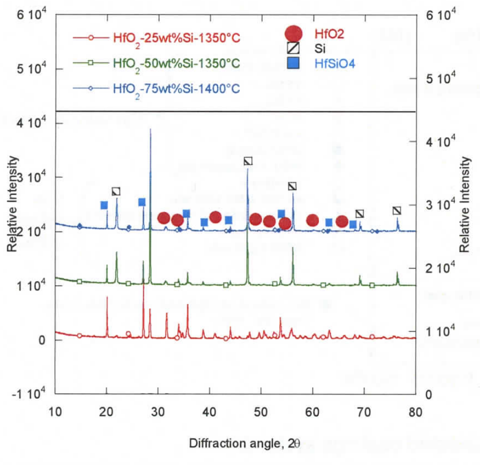
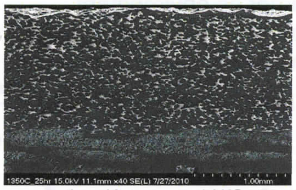
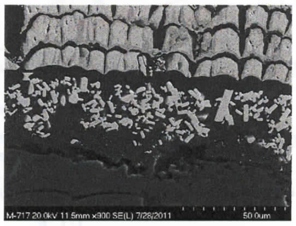
The NASA HfO_2+Si Bond Coats Showed Significantly Improved Temperature Capability as Compared to Si Bond Coats

— Higher stability and observed even after 1450°C+ temperature testing





Cross-section, Hot-pressed HfO_2-50wt%Si on CMC, 1350°C tested



Cross-section, Type II EB-PVD HfO_2-Si bond coat, 1500°C tested

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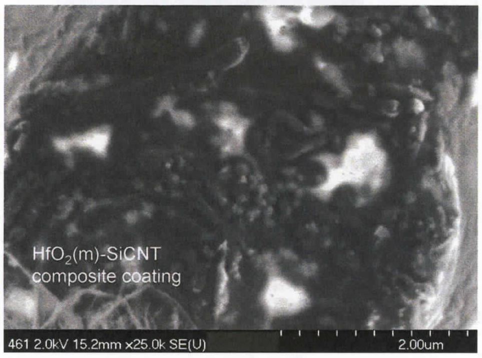
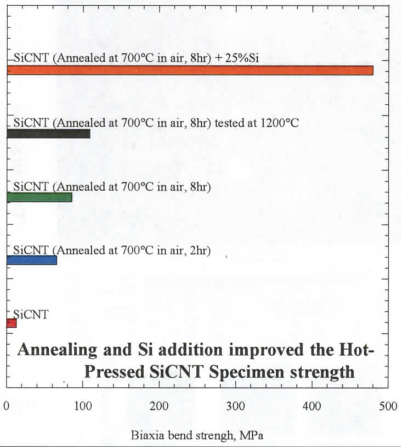
Advanced Next Generation 2700°F CMC Bond Coat Developments

- Develop advanced APS, PVD and polymer derived ceramic composite higher temperature bond coats for high strength and fatigue resistance
- Develop nanotube and nano-composite based coatings for high toughness



SiC nanotube (SiCNT) and HfO_2-based nanotube composite coatings



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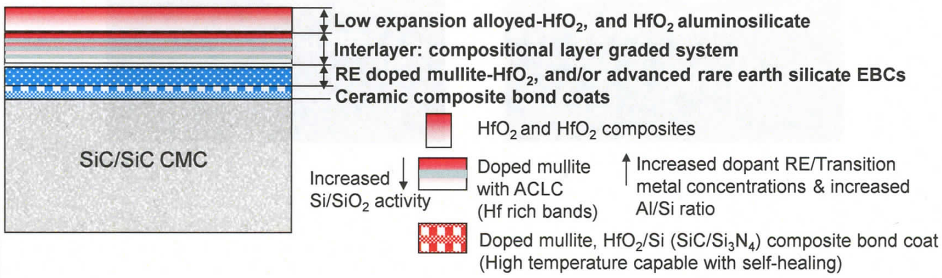
Advanced NASA EBC and EBC Top Coat Technologies

- Focus on high stability environmental barrier and advanced bond coat developments HfO_2 layer with graded interlayer,
  - BSAS, alloyed mullite and rare earth (RE) silicate EBCs
  - Broad range, new series compositions including HfO_2/ZrO_2, $ZrO2/HfO_2$-Rare Earth Silicates, HfO_2-Rare Earth Alumino-Silicates, and Rare Earth Alumino-Silicates
  - Alternating Composition Layered Coatings (ACLCs) and nano-composite coatings
  - Advanced processing approaches developed for vapor deposition, plasma spray, PVD, and polymer derived ceramics addressing high stability multi-component and nano-composite systems



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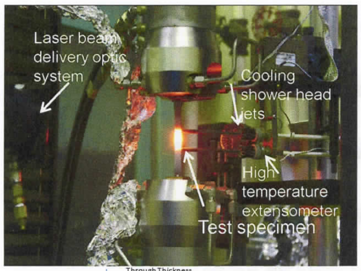
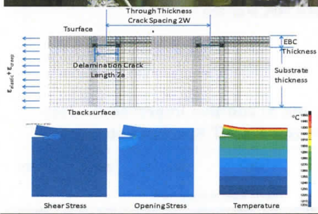
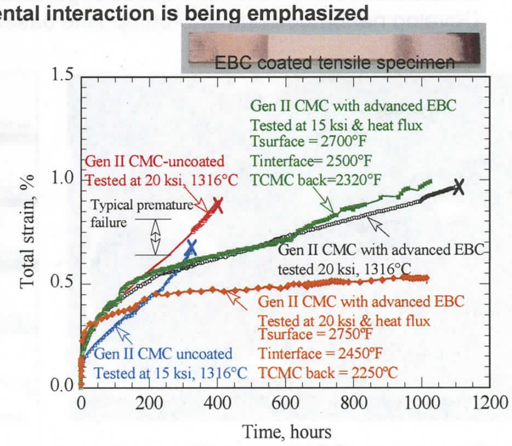
Thermal Gradient Tensile Creep Rupture Testing of Advanced Environmental Barrier Coating SiC/SiC CMCs

- Advanced high stability multi-component hafnia-rare earth silicate based turbine environmental barrier coatings being successfully tested for 1000 hr creep rupture
- EBC-CMC fatigue and environmental interaction is being emphasized







FEM models for delamination cracking under thermal gradient and tensile creep loading

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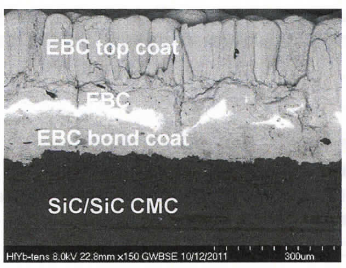
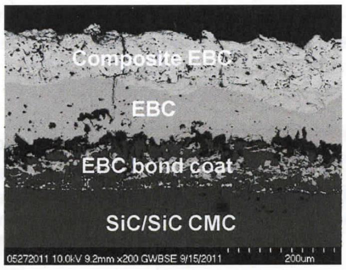
Thermal Gradient Tensile Creep Rupture Testing of Advanced Environmental Barrier Coating SiC/SiC CMCs - Continued

- Coating microstructures after 1000 hr, 1482°C (2700°F), 103 MPa (15 ksi) testing





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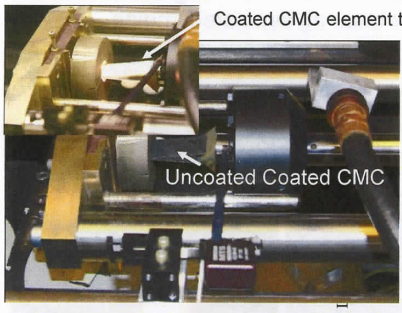
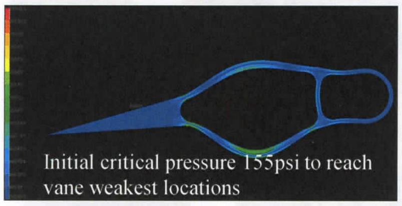
NASA Laser Heat Flux and Mechanical Testing of EBC-Subelements

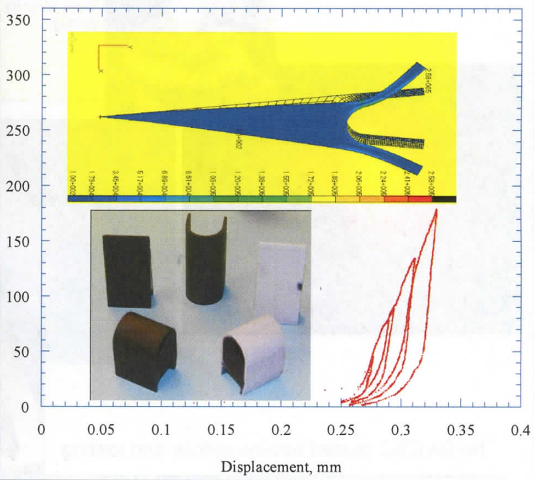
– CMC and EBC-coated subelement testing to simulate turbine vane loading

Coated CMC element tested at high temperature





Specimen GE TE specimen test



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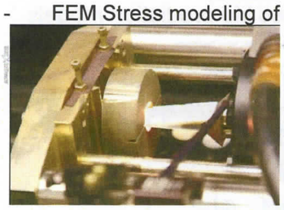
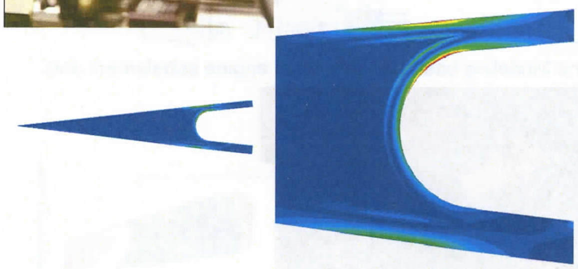
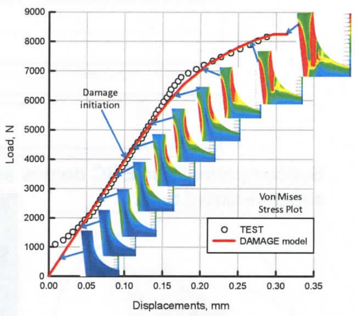
NASA Laser Heat Flux and Mechanical Testing of EBC-Subelements - Continued

- FEM Stress modeling of the EBC-CMC elements







FEM and damage model to simulate the subelement behavior

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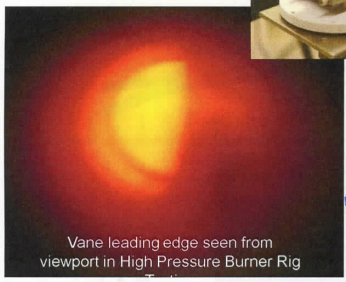
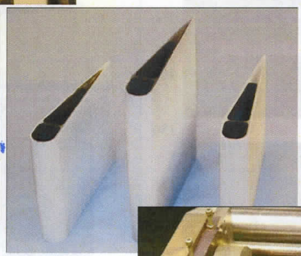
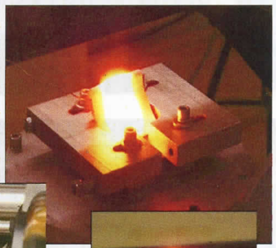
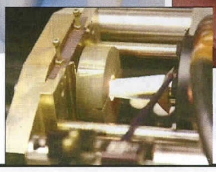
Advanced Rig Tests for SiC/SiC CMC EBC Demonstrations

– Advanced EBC coated turbine airfoils and subelements are being demonstrated in high pressure burner rig and high heat flux laser rig simulated engine environments









NASA EBC coated turbine airfoils and testing

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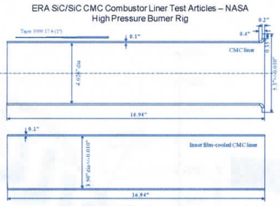
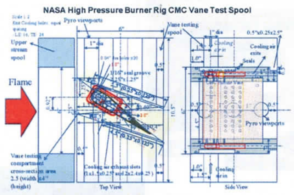
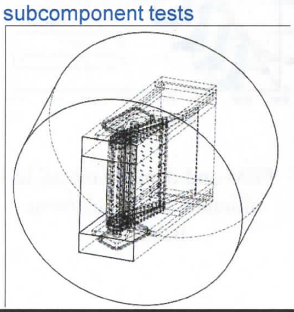
High Pressure Burner Rig Demonstrations for Validating EBC Coating and SiC/SiC Components (Gen II SiC/SiC CMC Subcomponents with Advanced Gen V EBCs)

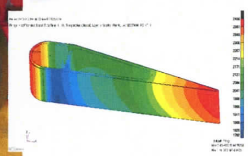
– Improve technology readiness and develop physics-based life prediction models





Subcomponent and EBC demos and Modeling based on simulated engine subelement and subcomponent tests





ERA CMC combustor liner and vane testing

National Aeronautics and Space Administration

Summary

- **Advanced high temperature SiC/SiC CMC environmental barrier coatings development**
  - Developed several series of new compositions for meeting various performance requirements
  - Emphasized advanced thinner coating configurations with long-term stability and durability
  - Demonstrated higher temperature capability, improved environmental stability and coating thermal - mechanical stress and creep-rupture resistance
  - Focused on coating composition developments and architecture designs to improve stability and durability at 2700-3000°F
- **Advanced high temperature SiC/SiC CMC environmental barrier coatings Testing Developments**
  - Developed advanced coating and subelement testing methods relevant to turbine CMC combustors and vanes, establishing initial property database, degradation and lifing prediction models
  - Developed advanced combustor and turbine vane EBC component technologies, and demonstrating the full feature EBC - CMC sub-components in relevant rig simulated engine environments

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